

# LOCAL VAPOR FUEL CELL

Patent Application of  
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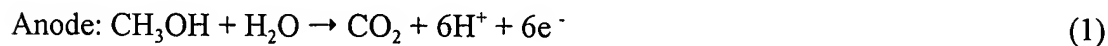
## FIELD OF THE INVENTION

This invention relates to a fuel cell operating on a hydrogen-rich organic fuel that is initially in a liquid form directly fed via diffusion into the anode; but the fuel turns into a vapor form when it comes in contact with the catalyst phase in the anode. The diffusion process is preferably driven by a capillarity force without using a liquid delivery pump. The invention specifically relates to a local vapor fuel cell (LVFC) such as a methanol vapor fuel cell (MVFC) or ethanol vapor fuel cell (EVFC).

## BACKGROUND OF THE INVENTION

A fuel cell is a device which converts the chemical energy into electricity. A fuel cell differs from a battery in that the fuel and oxidant of a fuel cell are supplied from sources that are external to the cell, which can generate power as long as the fuel and oxidant are supplied. A particularly useful fuel cell for powering portable electronic devices is a direct methanol fuel cell (DMFC) in which the fuel is a liquid methanol/water mixture and the oxidant is air or oxygen. Protons are formed by oxidation of methanol and water at the anode (fuel electrode) and pass through a proton-exchange membrane (or polymer electrolyte membrane, PEM) from the anode to the cathode (oxidant electrode). Electrons produced at the anode in the oxidation reaction flow in the external circuit to the cathode, driven by the difference in electric potential between the anode and cathode and can therefore do useful work.

The electrochemical reactions occurring in a direct methanol fuel cell which contains an acid electrolyte are:



1           The DMFC and other proton-exchange membrane fuel cells (PEMFCs) use a hydrated  
sheet of a perfluorinated acid-based ionomer membrane as a solid electrolyte. The electrodes  
each typically containing a catalyst phase (usually a thin catalyst layer) are intimately bonded to  
each side of the membrane. This membrane is commercially available from either DuPont (under  
the trade name Nafion<sup>®</sup>) or from Dow Chemical. Many catalysts to promote methanol oxidation  
6           (Reaction 1) have been evaluated. Examples include: (1) noble metals, (2) noble metal alloys,  
(3) alloys of noble metals with non-noble metals, (4) chemisorbed layers on Pt, (5) platinum with  
inorganic material, and (6) redox catalysts. Based on literature reports, Pt-Ru appears to be the  
best methanol-oxidation catalyst in acidic electrolytes.

11           The methanol/water feed to a DMFC may be in the liquid or vapor phase. If fuel cells  
using liquid fuel are available in small size, they would be able to power small-sized electronic  
devices for a long time. However, conventional DMFCs require pumps and blowers to feed  
liquid fuel to the fuel cell (e.g., S. Surampudi, et al., U.S. Pat. No. 6,248,460, June 19, 2001).  
The resulting power system is complex in structure and large in size. One way to overcome this  
problem is to utilize capillary action to feed liquid fuel, without using a liquid delivery pump.

16           However, a fuel cell of this type still has the following disadvantages: (1) poor  
performance due to low electrode reactivity and (2) low fuel utilization efficiency due to  
methanol cross-over from the anode through the electrolyte membrane to the cathode. This  
problem of methanol crossing over without being reacted is relatively more severe in a fuel cell  
with a pressurizing pump than in one without a pump.

21           It is believed that methanol vapor cells that operate at higher temperatures are  
advantageous in that the step of methanol ionization to produce protons (e.g., Reaction (1))  
proceeds more rapidly in these cells (e.g., as suggested in A. A. Kulikovsky, et al. "Two-  
dimensional simulation of direct methanol fuel cell," in Journal of the Electrochemical Society,  
147 (3) (2000) 953-959). Presumably, a higher temperature results in a higher catalytic electrode  
26           activity and the faster reaction leads to a reduction in fuel cross-over. However, in the  
conventional DMFC of a vapor feed type, methanol (as a liquid fuel) is introduced by a pump

1 into a vaporizer which vaporizes methanol with the resulting methanol vapor then being fed to  
the fuel cell by a blower. Unconsumed methanol vapor discharged from the outlet of the fuel  
electrode is recycled to the methanol tank through a condenser. This process needs a complex  
system (including a pump, a vaporizer, a blower, and a condenser) and, hence, is not suitable for  
powering small-sized electronic devices.

6 Tomimatsu, et al. (U.S. Pat. No. 6,447,941, Sep. 10, 2002) disclosed a fuel cell in the  
form of stacked unit cells each having a power generating section composed of a fuel electrode,  
an oxidant electrode, and an electrolyte plate held therebetween. The unit cells are placed on top  
of one another. In this fuel cell, a liquid fuel is introduced into each unit cell by the capillary  
action and evaporated in each unit cell in a fuel evaporating layer, so that the fuel electrode is  
11 supplied with the evaporated fuel. This is a very interesting fuel cell design since it makes use of  
the two sound approaches: liquid feed by capillary action and vapor state reaction. However, the  
fuel cell configuration is still too complex since each unit cell contains, among other layers,  
separate anode, liquid-permeating, and fuel evaporating layers. Too many layers make the fuel  
cell more tedious to make and more costly.

16 One object of the present invention is to provide a simpler configuration for a fuel cell  
that operates primarily on an organic fuel vapor. A specific object of the present invention is to  
provide a fuel cell that operates on a diffusion-fed methanol/water liquid fuel, which is then  
vaporized *in situ* at or near the anode catalyst prior to being ionized to produce protons.

21 From a systems standpoint, fuel cell operation on liquid methanol-water mixture  
containing some of the corresponding vapor is more advantageous. Therefore, another object of  
the present invention is to provide a fuel cell that operates on an organic fuel such as methanol  
that is at least partially vaporized when in contact with the anode catalyst.

## **BRIEF SUMMARY OF THE INVENTION**

26 The present invention provides a light-weight, compact fuel cell that is well-suited to  
powering portable electronic devices. The invented local vapor fuel cell (LVFC) is composed of

1 one or several unit cells that are physically stacked together and are electrically connected in  
series to provide a desired voltage level. Each unit cell comprises (A) an anode receiving a  
liquid fuel from a liquid fuel source substantially through diffusion; (B) an electrolyte plate (or  
proton exchange membrane, PEM) having a first surface adjacent to the anode; and (C) a cathode  
adjacent to a second surface of the electrolyte plate and opposite to the anode. The anode is  
6 provided with a heating environment to at least partially vaporize the liquid fuel inside the anode  
to produce fuel vapor near or at the catalyst phase. The catalyst phase ionizes the fuel vapor or  
the vapor-liquid mixture to produce protons that migrate through the PEM (e.g., a polymer  
electrolyte membrane) to the cathode side. The catalyst phase preferably forms a thin layer  
adjacent to the electrolyte plate.

11 A special feature of the presently invented LVFC is that the fuel (e.g., methanol/water  
mixture) is supplied initially in a liquid form into the anode primarily via diffusion, preferably  
under the action of a capillary force. To accomplish this function, the anode may be made to  
comprise a porous fuel-permeating material being in fluid communication with a liquid fuel  
source and receiving the liquid fuel therefrom. However, the liquid fuel is vaporized, partially or  
16 completely, just before or when it comes in contact with a catalyst. This heated environment  
allows the fuel vapor or vapor-liquid mixture to react at a higher temperature in a more efficient  
manner for proton generation. The heating environment may receive the heat generated by the  
electrochemical reactions occurring at the cathode. Alternatively or additionally, the heating  
environment may receive the heat from joule heating by passing a current through the anode.  
21 This current may flow through a thin wire that is preferably localized in the vicinity of the  
catalyst phase. The current may be provided intermittently on demand with the assistance of a  
temperature sensor and a control circuit. Other preferred embodiments of the present invention  
include several configurations of multiple-cell fuel cell devices with each of these cells  
exhibiting the aforementioned features.

26 The LVFC that relies on a heating element to provide additional heat to help locally  
vaporize the liquid fuel at the anode catalyst phase is hereinafter referred to as an extrinsically  
controlled LVFC or actively controlled LVFC. The FVFC that relies primarily on the internally

1 generated heat due to electrode reactions is referred to as an intrinsically controlled LVFC or  
passively controlled LVFC. The advantages of such an extrinsically controlled LVFC includes:

- 6 (1) The amount of electrical power needed to generate the local joule heat represents only a  
very small fraction of the total amount of power that a fuel cell can provide. The resulting  
improvement in the power output considerably more than compensates for the power loss  
that is required to locally vaporize the fuel.
- 11 (2) Since the heat is generated locally to vaporize the liquid fuel near the anode, there is very  
little heat loss to the outside environment. By contrast, the current direct methanol fuel  
cell of a direct vapor feed type requires a vaporizer and a blower to deliver the vaporized  
fuel from the vaporizer to the fuel cell body through a pipe. This procedure is prone to  
heat energy loss. Besides, the combined vaporizer-blower-pipe makes the fuel cell bulky  
and heavy.
- 16 (3) The vaporous fuel at a higher temperature means a faster and more efficient catalytic  
reaction at the anode catalyst site. This reaction condition promotes essentially full  
conversion of the fuel into the desired electrons and protons, thereby minimizing  
methanol crossover from the anode to the cathode side through the electrolyte. A reduced  
methanol crossover implies not only a higher electro-oxidation of methanol-water fuel at  
the anode, but also less methanol “poisoning” of the cathode catalyst which allows better  
contacts between oxygen and the cathode catalysts.
- 21 (4) The liquid fuel feeding via capillarity pressure-driven diffusion of liquid fuel through the  
anode makes it possible to have a highly compact fuel cell assembly due to the fact that  
no liquid fuel pump or vapor fuel blower is needed in the LVFC.

The above extrinsically controlled LVFC, in practice, needs a temperature sensor, a heating  
element, and a simple temperature-controlling circuit. The intrinsically controlled LVFC has the  
following added advantage:

- 26 (5) The fuel cell geometry (size and shape) and material compositions involved can be  
selected in such a manner that the methanol-water fuel is in a vaporous state locally at the  
anode catalyst phase, but in a liquid state at other locations of the anode side. The needed  
heat comes primarily from the inherent electrode reactions. This feature will allow an  
intrinsically controlled LVFC to enjoy the same advantages (3) and (4) cited above for the

1 extrinsically controlled LVFC, but without having to implement a temperature sensor,  
heater, and temperature controlling circuit.

## **BRIEF DESCRIPTION OF THE DRAWINGS**

FIG.1 A cross sectional view showing the components of a prior-art fuel cell that operates on  
fuel vapor.

6 FIG.2 A cross sectional view showing the structure of the components of a fuel cell containing  
anode catalysts that operate locally on a fuel vapor or vapor-liquid mixture.

FIG.3 A perspective view showing the components of the fuel cell of the present invention.

FIG.4 A cross sectional view showing the structure of the components of a fuel cell wherein the  
anode contains a heating element to help vaporize the fuel.

11 FIG.5 The voltage-current responses of two fuel cells.

## **DETAILED DESCRIPTION OF THE INVENTION**

In order to best illustrate the features and advantages of the presently invented fuel cells,  
relevant prior-art fuel cells will be briefly discussed first. An example of prior-art fuel cells that  
operate on organic fuel vapor is presented in FIG.1 (Tomimatsu, et al., U.S. Pat. No. 6,447,941,  
16 Sep. 10, 2002). This cross sectional view of the structure includes an electrolyte plate 1, which is  
held between a fuel electrode (anode) 2 and an oxidant electrode (cathode) 3. The electrolyte  
plate 1, the anode 2, and the cathode 3 constitute the power generating section 4. The anode 2  
and the cathode 3 are made of an electrically conductive porous material so that they allow the  
passage of fuel and oxidant gas as well as electrons.

21 This prior-art fuel cell contains a fuel-permeating layer 6 and a separate fuel evaporating  
layer 7. Layer 6 introduces liquid fuel into the fuel cell by the capillary action. The fuel  
evaporating layer 7 is interposed between the anode 2 and the liquid fuel-permeating layer 6.  
Layer 7 evaporates the liquid fuel which is introduced into the fuel cell and feeds the fuel in the  
form of vapor to the anode 2, which is another separate layer. Layers 2, 1, and 3 together form a  
26 power-generating section 4. Layers 3, 1, 2, 7, 6 together constitute a "unit cell". Several of these  
unit cells are placed on top of another consecutively, with a separator 5 interposed between them,

1 so that they constitute a stack 9 which is the fuel cell proper. The grooves 8 through which the  
oxidant gas is supplied are formed continuously in that surface of the separator 5 which is in  
contact with the cathode 3.

It is clear that this prior-art fuel cell, although much simplified over other existing fuel  
cells, still has a relatively complex configuration and has too many layers. By contrast, we have  
6 integrated the fuel-permeating layer, the fuel evaporating layer, and the anode layer into just one  
anode layer 12 (FIG.2). Preferably, the catalyst phase in the anode layer 12 is arranged to be in a  
close proximity to or in an intimate contact with the electrolyte layer 11. The catalyst phase may  
be essentially a thin layer (of a nanometer thickness) at the edge of the anode layer 12 facing the  
electrolyte layer 11. In such an arrangement, the reaction heat generated by the inherent electro-  
11 chemical reactions can easily reach the catalyst phase to help vaporize the fuel that has permeated  
to the vicinity of the catalyst. It is not necessary to vaporize all the liquid fuel that has permeated  
into the anode layer, only the portion close to or in contact with the catalyst (hence, the name  
“local vapor fuel cell”).

It may be noted that, in the aforementioned prior-art fuel cell (FIG.1), the fuel permeating  
16 layer 6 is isolated or separated from the reaction electrodes in such a distance that it cannot  
effectively receive the reaction heat generated by the cell reactions. The prior-art inventors also  
failed to recognize that a fuel vapor-liquid mixture works nearly as well as a pure vapor in the  
anode reaction for proton production, which we surprisingly found to be the case. It is desirable  
to select the electrolyte layer thickness and other reaction conditions such that the catalyst phase  
21 is heated by the reaction heat to a temperature significantly higher than 64°C (the boiling point of  
methanol) in the case of using methanol/water mixture as the liquid fuel. The local reaction  
temperature at the anode catalyst for the methanol fuel cell is preferably in the range of 80-  
150°C, but most preferably in the range of 95-130°C. Although a higher temperature is generally  
26 preferred for a higher efficiency, an excessively high local temperature can spill over to other  
portions of the anode, making it more difficult to maintain the fuel in other portions of the anode  
(than the catalyst layer area) in a liquid state.

1           Alternatively, one may choose to introduce a thin metal wire or conductive fiber (e.g., 24  
in FIG.4) into the catalyst side of the anode layer to help vaporize the liquid fuel in the vicinity of  
the catalyst phase (26 in FIG.4). A small amount of current may be allowed to flow through this  
wire or fiber to produce joule heat. A minute temperature sensor element (e.g., a thin  
thermocouple wire) may be placed inside the anode to monitor the catalyst phase temperature.  
6       Temperature monitoring and control devices or circuits are well-known in the art. Such a  
combined heating element-sensor arrangement is advantageous in that additional heat may be  
supplied to vaporize more fuel on demand (e.g., when needed, more current may be supplied to  
the external load by vaporizing the fuel at a faster rate and allowing the reactions to proceed at a  
higher temperature). With such an added adaptability, the fuel cell essentially becomes a smart,  
11       actively controlled power source. A simple logic circuit may be added as a part of the fuel cell  
voltage regulator or control circuit that is normally installed in a fuel cell for electronic device  
applications.

          In one special fuel cell design of Tomimatsu, et al., there is a combined fuel permeating-  
evaporating member, which has a fuel permeating portion and a fuel evaporating portion.  
16       However, this combined layer has to be made to contain specially machined holes and are  
complex in configuration. This requirement makes this layer and the whole fuel cell assembly  
more difficult and costly to produce despite the notion that this combination makes it possible to  
decrease the thickness of the member, as compared with the case where each of these fuel  
permeating member and the fuel evaporating member are formed of individual members  
21       separately.

          As a means to feed liquid fuel to the anode layer 12 from a fuel source, there is formed a  
liquid fuel passage 20 along at least one side of the stack 19 (FIG.2). Upon introduction into the  
liquid fuel passage 20, the liquid fuel is fed to the fuel permeating material of the anode layer 12  
by the capillary action from the side of the stack 19. In order to supply liquid fuel to the fuel  
26       permeating material by the capillary action, the fuel cell is constructed such that the liquid fuel  
which has been introduced into the liquid fuel passage 20 comes in direct contact with the end  
surface of the anode layer 12.



1           The separator **15** (when existing) and the anode layer **12** (including the fuel permeating  
material therein) are each made of an electrically conductive material so that they function as a  
current collector to transmit electrons generated in the fuel cell. The fuel cell in this example  
(FIG.2) has the separator **15** which functions also as a channel to permit the oxidant gas to flow  
therethrough into the cathode. The advantages of using the multi-purpose separator **15** include a  
6 size reduction and reduction in the number of parts used.

          The liquid fuel passage **20** may be constructed such that the liquid fuel is introduced from  
a fuel source (not shown) into the fuel permeating material of the anode layer **12** by the capillary  
action. One way to supply liquid fuel from the fuel source to the liquid fuel passage **20** is to  
permit the liquid fuel to drop spontaneously by gravity and to enter the liquid fuel passage **20**.  
11 This gravitational method offers the advantage of assuring the introduction of the liquid fuel into  
the liquid fuel passage **20**, although it requires that the fuel source be positioned above the top of  
the stack **19**. Another method is to introduce the liquid fuel from the liquid fuel source by the  
capillary action of the liquid fuel passage **20**. This method does not require that the joint between  
the liquid fuel source and the liquid fuel passage **20** (or the fuel entrance of the liquid fuel  
16 passage **20**) be arranged above the top of the stack **19**. When combined with the gravitational  
method, this method offers the advantage of being free to install the fuel source at any place or  
orientation. The liquid fuel passage **20** may be formed on one side or both sides of the stack **19**.

          The fuel source described above may be made detachable from the fuel cell proper, so  
that the fuel cell can be run for a prolonged period of time by intermittently replenishing the fuel  
21 source. The feeding of the liquid fuel from the fuel source to the liquid fuel passage **20** may be  
accomplished by gravity or by pressure in the source. An alternative feeding method is to extract  
the liquid fuel by the capillary action of the liquid fuel passage **20**.

          The structure of the fuel permeating material in the anode layer is not specifically  
restricted as far as it permits the liquid fuel to permeate through it by the capillary action. It may  
26 be made of a porous material, cotton, non-woven fabric, highly porous paper, or woven cloth of  
fibers. The fuel permeating material draws liquid fuel into it by the capillary action. For the

1 effective use of the capillary action, the fuel-permeating porous material should be formed such  
that its pores are interconnected and its pores have an adequate pore diameter. The porous  
material may have any pore diameter which is not specifically restricted, as long as it permits the  
liquid fuel to be drawn into the liquid fuel passage 20. However, the pore diameter is preferably  
0.01 to 150  $\mu\text{m}$  in view of the capillary action of the liquid fuel passage 20. Furthermore, the  
6 pore volume as an index of pore continuity should preferably be 20 to 90% of the porous  
material. With a pore diameter smaller than 0.01  $\mu\text{m}$ , it becomes difficult for liquid fuel to  
diffuse through the pores; this could be understood from the well-known Darcy's Law that  
describes the diffusion behavior of a liquid through a porous medium. With a pore diameter  
larger than 150  $\mu\text{m}$  the porous material is poor in its capillary action. With a pore volume less  
11 than 20%, the porous material has closed pores in a higher proportion and hence is poor in its  
capillary action. With a pore volume fraction greater than 90%, the porous material has a higher  
proportion of continuous pores but is poor in strength and present difficulties in fabrication.  
Practically, the pore diameter should preferably be 0.5 to 100  $\mu\text{m}$  and the pore volume fraction  
should preferably be 30 to 75%.

16 Liquid fuel feeding grooves 21 may be formed in the surface of the separator 15 (serving  
also as the channel) in contact with the fuel permeating material of the anode layer 12, as shown  
in FIG.3. The capillary action of these grooves may be used to draw liquid fuel into the fuel  
permeating material also through the capillary action. In this case, the liquid fuel passage 20  
should be formed such that the open ends of the liquid fuel feeding grooves 21 come into direct  
21 contact with the liquid fuel passage 20 (indicated in FIG.2, but not FIG.3). Alternatively, it is  
possible to use the capillary action of the liquid fuel feeding grooves 21 in combination with the  
capillary action of the porous material constituting the fuel permeating material of the anode  
layer 12.

26 It may be noted that the liquid fuel feeding grooves 21 are not specifically restricted in  
configuration as long as they are capable of producing an adequate capillary action. However,  
they should be formed such that their capillary action is smaller than that of the fuel permeating  
material of the anode layer. Otherwise, the liquid fuel will not be fed from the liquid fuel passage

1 20 to the fuel permeating material. The liquid fuel feeding grooves 21 are intended to extract  
liquid fuel from the liquid fuel passage 20 by their capillary action. Therefore, they should be  
formed such that their capillary action is greater than that of the liquid fuel passage 20 in the case  
where the liquid fuel is introduced from the fuel source into the liquid fuel passage 20 by its  
capillary action. Thus, the configuration of the liquid fuel feeding grooves 21 should be formed  
6 in accordance with the configurations of the porous material constituting the fuel permeating  
material of the anode layer 12 and the liquid fuel passage 20.

The separator 15 serving also as the channel is provided with the liquid fuel feeding  
grooves 21 extending in the horizontal direction, as mentioned above. This construction permits  
the liquid fuel to be fed from the entire surface of the end of the anode 12 to the fuel permeating  
11 material inside the anode layer and also permits the liquid fuel to be fed in the lateral direction  
across the anode layer through the grooves 21. This makes it possible to feed liquid fuel more  
smoothly from the liquid fuel passage 20 to the fuel permeating material.

In the aforementioned example, the separator 15 serving also as the channel is provided  
with both the oxidant gas feeding grooves 18 and the liquid fuel feeding grooves 21.  
16 Alternatively, the anode layer 12 and the cathode 13 may be individually provided with channels.  
In this case, one set of channels should be separated from another set of channels by an  
electrically conductive plate to block the passage of gas, or the holes on the surface of at least one  
set of channels should be closed, so that the liquid fuel is separated from the oxidant gas. In order  
to decrease the number of parts used and to reduce the size of the fuel cell, it is desirable to use  
21 the separator containing both types of channels.

The examples described above are directed to a fuel cell which has the stacks 19 (each  
composed of a power generating section 14) which are placed on top of the other, with each stack  
separated by the separator 15. However, the fuel cell of the present invention does not  
necessarily need the separator channels. In this case, the oxidant gas feeding grooves 18 may be  
26 continuous ones formed in the surface in contact with the cathode.

1 In another embodiment of the present invention, the fuel cell may have a liquid fuel-  
holding portion positioned on the anode (in contact with one of the two primary or larger-area  
surfaces of the anode, rather than on one end or both ends of the anode). In this case, the fuel cell  
comprises (a) a cathode, (b) an electrolyte plate disposed on the cathode, (c) an anode disposed  
on the electrolyte plate and configured to be supplied with a liquid fuel, and (d) a liquid fuel-  
6 holding portion disposed on the anode. The anode is provided with a heating environment to at  
least partially vaporize the liquid fuel inside the anode and the anode further comprises a catalyst  
phase to ionize the fuel in a vapor or vapor-liquid mixture form to produce protons. Other  
features and operating methods of this fuel cell are similar to those discussed earlier in other  
embodiments.

#### 11 Example 1

A fuel cell was prepared as follows: Graphite flakes were subjected to a ball-milling  
treatment to obtain fine particles of several microns in size. These fine particles were mixed with  
a phenolic resin to obtain a slurry mixture. Chopped carbon fibers were then mixed with the  
slurry mixture to prepare a composite, which was then molded at a temperature of 250°C for one  
16 hour with a hot press and then partially carbonized first at 350°C and then at 600°C for  
approximately two hours. These treatments lead to the formation of a thin, highly porous carbon  
structure having an average pore diameter of 60  $\mu\text{m}$  and a porosity of approximately 65%. A  
sheet of this carbon composite structure was coated on one side with a Pt-Ru catalyst to give an  
anode of 32 mm x 32 mm in dimensions. A carbon cloth was coated with a platinum black  
21 catalyst to give a cathode also of 32 mm x 32 mm. A polymer electrolyte membrane,  
poly(perfluorosulfonic acid) ionomer, was held between the anode and the cathode, with the  
catalyst layers in contact with the electrolyte membrane. The assembly was joined together by  
hot-pressing at 120°C for 5 minutes under a pressure of 100 kg/cm<sup>2</sup>, to give a power generating  
section. The resulting assembly was held between a cathode holder and an anode holder, the  
26 former having oxidant gas feeding grooves each having a depth of 2 mm and a width of 1 mm.  
The obtained unit cell has a reaction area of 10 cm<sup>2</sup>. The fuel cell was supplied with a  
methanol/water mixture at an 1:1 molar ratio as a liquid fuel. The liquid fuel was introduced by  
the capillary action through the side of the anode. The air at 1 atm as an oxidant gas was fed into

1 the gas channels at a flow rate of 100 mL/min so that the fuel cell generated electricity at 76°C.  
This fuel cell gave a current-voltage characteristic as shown in Curve A of FIG.5.

#### Comparative Example 1

6 A fuel cell of the prior-art type was prepared as follows. An assembly for the power  
generating section was prepared in the same way as in Example 1. However, the power  
generating section was further combined with a fuel evaporating layer and a fuel permeating  
layer as shown in FIG.1. The fuel evaporating layer is a porous carbon plate having an average  
pore diameter of 100  $\mu$  and a porosity of 70%. The fuel permeating layer is a porous carbon plate  
having an average pore diameter of 5  $\mu$ m and a porosity of 40%. The liquid fuel cell thus  
obtained was supplied with a methanol-water mixture mixed at a 1:1 molar ratio as a liquid fuel.  
11 The liquid fuel was introduced by the capillary action through the side of the anode. The air at 1  
atm as an oxidant gas was fed into the gas channels at a flow rate of 100 mL/min so that the fuel  
cell generated electricity at 79°C (measured at the catalyst/electrolyte interface). This fuel cell  
gave a current-voltage characteristic as indicated in Curve B of FIG.5.

16 The two curves shown in FIG.5 demonstrate that the fuel cells in both examples produce  
a stable output voltage until the current reaches about 5 amps. This implies that it may not be  
necessary to have separate liquid fuel-permeating and fuel-vaporizing layers (that would make  
the fuel cell more bulky, heavy and expensive). It appears that as long as the catalyst phase  
works primarily with a fuel vapor, the fuel cell is capable of achieving a high reactivity and low  
methanol cross-over (from the anode to the cathode side).

#### 21 Example 2

26 A series of fuel cells were prepared and operated in the same way as in Example 1, with  
the exception that a thin copper wire was introduced into and out of the anode at a location very  
close to the polymer electrolyte layer (and, hence, close to the catalyst layer). A desired amount  
of current was fed into this zone to vary the fuel temperature between approximately 64°C (the  
boiling point of methanol) and 130°C (30° above 100°C, the boiling point of water) while the  
exterior temperature was maintained at a relatively low level by blowing a cool air to the fuel cell

1 while in operation. It was found that, in general, the higher the reaction temperature, the more  
stable the voltage was. A higher local temperature near the catalyst phase implies not only a  
higher vapor content, but also a higher electrolytic reaction rate at the anode (Reaction 1). Both  
factors are in favor of a more stable voltage response as a function of current by way of an  
increased reactivity (faster and more efficient fuel conversion) and reduced chance of fuel cross-  
6 over.

It may be noted that, although the examples given herein are based on the methanol/  
water mixture as the liquid fuel, the presently invented fuel cell is not limited to this particular  
type of fuel. The present fuel cell can operate on any organic fuel that has a high hydrogen  
content (e.g., ethanol and hexane) and can be fed in a liquid form into the anode through  
11 diffusion and then vaporized locally at the catalyst phase. For instance, the ethanol/water  
mixture can be used in the fuel cell when the catalyst zone is heated to a temperature above 78°C,  
up to approximately up to 130°C with poly(perfluorosulfonic acid) being the PEM used. This  
upper temperature appears to be limited by the working temperature of the polymer electrolyte.  
With a more thermally stable polymer electrolyte membrane, such as sulfonated polyimide, the  
16 vapor fuel temperature can be pushed even higher. A temperature up to 150°C (approximately  
50 degrees above the boiling temperature of water) was found to work well.

Hence, another embodiment of the present invention is a fuel cell which comprises (A) an  
anode comprising a catalyst phase and receiving a liquid fuel from a liquid fuel source (with the  
liquid fuel having a minimum boiling point  $T_b(\text{min})$  and a maximum boiling point  $T_b(\text{max})$ ); (B)  
21 an ion exchange electrolyte having a first surface adjacent to the anode; and (C) a cathode  
adjacent to a second surface of the electrolyte. In this fuel cell, the anode is provided with a  
heating environment inside the anode to ensure that the catalyst phase operates at a temperature  
between  $T_b(\text{min})$  and approximately  $[T_b(\text{max}) + 50 \text{ degrees C}]$  to ionize the fuel to produce ions  
that move across the ion exchange electrolyte.

26 It is known that water has a boiling point of 100°C, methanol has a boiling point of  
approximately 64°, and ethanol has a boiling point of approximately 78.5°C. For a fuel cell fed

1 with a mixture of water and methanol, the catalyst phase operates on methanol in a vaporous  
state and water in substantially liquid state if the local temperature is in the range of 64°C and  
100°C. Both methanol and water will be substantially vaporized if the catalyst temperature  
exceeds 100°C. It is particularly advantageous to allow the catalyst phase to operate at a local  
6 temperature of slightly higher than 100°C, but preferably not higher than 130°C with an ion  
exchange electrolyte comprising poly(perfluorosulfonic acid) as the primary ion-conducting  
medium. For the ethanol/water mixture, the catalyst operating temperature is in the range of  
78°C and 150°C, but preferably in the range of 100°C and 130°C. For a three-component  
mixture (water + methanol + ethanol), the catalyst operating temperature is in the range of 64°C  
and 150°C, preferably in the range of 78°C and 130°C, but most preferably between 100°C and  
11 130°C.